PROPERTIES OF HYDROMAGNETIC WAVES IN THE POLAR CAPS: ULYSSES

E. J. Smith[1], M. Neugebauer[1], B. T. Tsurutani[1], A. Balogh[2], R. Forsyth[2], D. McComas[3]

[1]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109
[2]The Blackett Laboratory, Imperial College, London SW72BZ
[3]Space and Atmospheric Sciences Group, Los Alamos National Laboratory, Los Alamos, NM 87545

ABSTRACT

Properties of the large amplitude Alfvén waves which are a dominant feature of the high latitude solar wind have been studied during the pole-to-pole passage of Ulysses. In addition, an effort has begun to identify magnetosonic waves at high latitude in spite of their expected small amplitude and the presence of the large amplitude Alfvén waves. The power in the latter is essentially the same in both solar hemispheres without evidence of any significant north-south asymmetry. The increased power as Ulysses approached the poles is not, in fact, dependent on latitude but is caused by a power law dependence on distance. The Alfvénicity of the fluctuations, as indicated by the covariance of the field and velocity, increases to high levels (0.8) at high latitudes. Principal axis analyses indicate that the field vector appears to wander randomly over a hemisphere whose radius is the nearly constant field magnitude. This behavior is consistent with a stochastic model introduced by Barnes as demonstrated by a statistical analysis of the field variations observed by Ulysses. The principal axis analysis also shows that the direction associated with the minimum eigenvalue is nearly radial. The strategy for identifying magnetosonic waves involves searching for them in the weak interaction regions accompanying microstreams. Simultaneous variations in the magnetic, kinetic, and total pressures are qualitatively consistent with the presence of magnetosonic waves.

INI'RODUCTION

The following study uses a combined set of magnetic field and plasma data from the Ulysses mission. Both kinds of data are needed in order to study waves. Large amplitude Alfvén waves are a dominant feature of the fast, high-latitude wind (Smith *et al.*, 1995b). Magneto sonic waves have been sought with little, if any, success in the ecliptic, e.g., in Helios data (Tu and Marsch, 1994). The reason is believed to be that magnetosonic waves are strongly damped. Nevertheless, their identification and the determination of their properties would be of obvious scientific interest and could also contribute to the complementary view of the solar wind fluctuations as turbulence rather than waves. Since magnetosonic wave amplitudes

are expected to be small and to be embedded in a sea of much larger Alfvén waves, the principal task is their unambiguous identification.

ALFVÉN WAVES

An overview of the waves observed by Ulysses in the south and north solar hemispheres is shown as Figure 1, a plot of one of the variances as a function of time with latitude shown at the top. The parameter shown, $\sigma_S^2 = \sigma_R^2 + \sigma_T^2 + \sigma_N^2$, is the sum of the variances in the three coordinate directions, radial, azimuthal, and meridional or north-south, computed hourly and averaged over successive days. It is a measure of the power in the changes in field direction and is dominated by the Alfvén waves. Actually, the parameter has been normalized by dividing by the square of the field magnitude, or B^2, over the same intervals. This normalization has been found useful in studying radial gradients of the fluctuations in the outer heliosphere where this ratio tends to be an invariant, Figure 1 shows that the average value of

Fig, 1. Normalized power in the directional field changes.

this ratio, σ_S^2 / B^2, is constant anti of equal magnitude in both the south and north hemispheres. The abrupt decrease and following increase in the center of the plot is associated with the return to the slow, low-latitude solar wind as the spacecraft crossed the heliographic equator near perihelion. Overall, no significant difference in the Alfvén waves has been found between hemispheres, or, alternatively, no north/south asymmetry is evident.
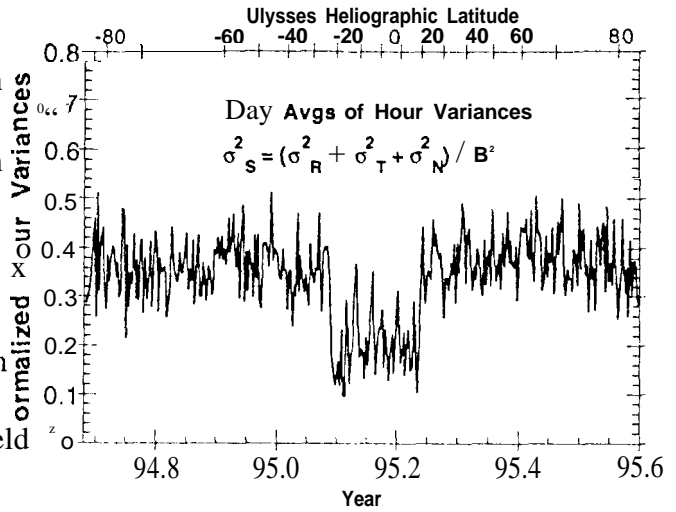
Since Ulysses is traveling toward and then away from perihelion during the interval shown, both σ_S^2 and 13^2 increase and then decrease. Figure 2 is a log-log plot of the sum of the variances, σ_S^2, averaged over longer intervals of 25 days, or approximately one solar rotation, as a function of radial distance. The values are low in the southern hemisphere as indicated, increase to a peak at perihelion (-1.3 AU) and then decrease in the northern hemisphere as the spacecraft returns to the outer heliosphere. The data in the two hemispheres overlap nicely indicating that the wave amplitudes are symmetric in the two hemispheres. Another feature of this plot is the straightline dependence of log σ_S^2 on log r with a slope of approximately -3. This proportionality of

Fig. 2. Dependence of the hourly variances on radial distance.

σ_S^2 to r^{-3} is what would be expected on the basis of the WKB approximation to the decrease in wave amplitude assuming the Alfvén waves are generated near the Sun in the solar wind source region (Hollweg,
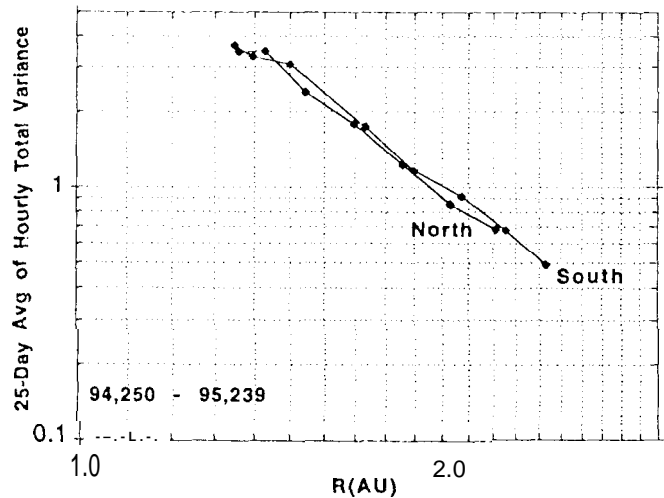
1980). However, this relationship holds only for the relatively short period waves analyzed here but is not satisfied for longer periods of tens of hours as has been shown by Forsyth *et al. (1996)* and by Jokipii *et al.* (1995).

The principal feature which identifies the waves as Alfvénic is the excellent correlation between the transverse perturbations in the solar wind velocity, δV, and the vector magnetic field, δB. A sample correlogram is shown in Figure 3 in which V_N is plotted against B_N. The straightline fit leads to a correlation coefficient of 0.72 and to a slope of 24.0 km/s ·nT. Since the average field magnitude during this interval was -1.0 nT, the modified Alfvén speed, A $C_A = B \,\delta V/\delta B = 24$ km/s where $A = 1 - 4\pi\,(P_{\parallel} - P_{\perp})/B^2$, is a measure of the anisotropy in the solar wind pressures parallel and perpendicular to the magnetic field. The average value of the measured solar wind density, $p = 0.3$ cm^{-3}, implies an Alfvén speed of 48 km/s so that A = *0.5.* Reduction of the Alfvén wave speed try the anisotropy is a typical feature of the high-latitude Alfvén waves (Goldstein *et al.*, 1995).

Ulysses, 1994, **Days** 182-212
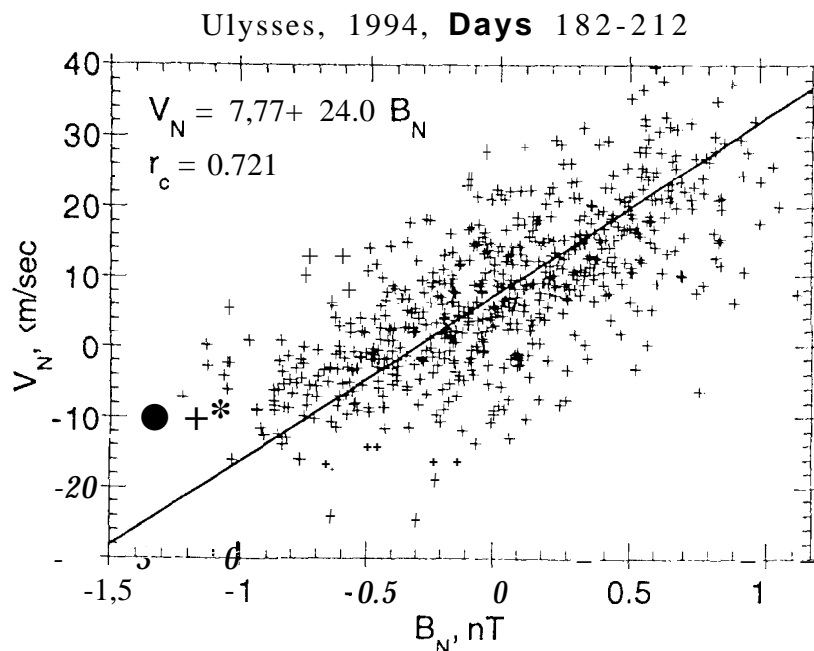
$V_N = 7.77 + 24.0\ B_N$

$r_c = 0.721$

Fig. 3. Correlation between fluctuations in the field and solar wind velocity.

The cross-correlations between V_N-B_N and V_T-B_T over an interval of 3.5 years, from the Jupiter encounter to the passages over the south and north polar caps, are shown in Figure 4. The cross-correlations are approximately zero until Ulysses passed below the Heliospheric Current Sheet (HCS) at a latitude of -30° (Smith *et al., 1993),* and then began to rise monotonically in the fast high latitude wind up to a maximum value of -0.8. 'I'he values remained high until --30° is reached once again and then dropped precipitously as the equator was crossed during the Fast Latitude Scan (Smith *et al., 1995a).* Upon crossing into the north hemisphere, the sign of the cross-correlation reversed, along with the ambient magnetic field which, as expected, is positive or outward in the north. The negative sign combined with the outward field implies that the waves are propagating outward and away from the Sun just as in the south. Although 26-day averages of hourly averages of the cross-correlations are shown, it is known that a high correlation, indicative of Alfvén waves, persists at much shorter and much longer intervals. A coherency analysis has shown that a high

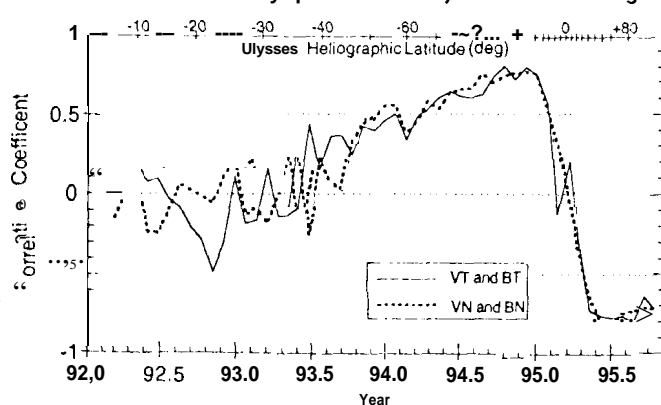Correlation for 26-day perioda of Ulysses hour averages

Fig. 4. Correlation coefficients of the field-velocity components from the equator to the pole.

correlation of --0.8 and a linear phase relation are maintained down to periods of 10 hours. The appearance of the waves is the same in both hemispheres and in the most recent data as Ulysses has descended to -35° N and gone outward to 4.0 AU.

Much basic information about waves, in general, can be obtained by transforming the field variations into principal axis coordinates. It is customary to use the formulation introduced by Sonnerup in which average values of the field components are subtracted and the eigenvalues and eigenvectors corresponding to the largest, intermediate and smallest variances are found (Sonnerup and Cahill, 1967). The interpretation of the direction of minimum variance as the direction of the k vector, where $k = \omega/C_A$ and CA is the phase velocity of the wave, has been disputed for many years without a satisfactory resolution. Nevertheless, it is informative to view the variations in principal axis coordinates as, for example, in Figure 5. The upper half figure shows the locii of the end of the field vector as projected into the plane formed by the eigenvectors corresponding to the largest (I) and intermediate (J) eigenvalues. Although the specific interval covered is 14 hours, the field variances seen here are typical of shorter, as well as longer, intervals. The field appears to wander randomly over this plane with the maximum excursions lying along the circumference of the circle whose radius is the same as the average field magnitude, B.

The lower half panel shows the orthogonal view with the vertical axis in the direction of the eigenvector (K) corresponding to the minimum eigenvalue or minimum variance. It might be expected that the excursions in this representation would have yielded a variation nearly parallel to the IJ plane or having a fairly constant B_K component. Such would be expected for a series of parallel rotational discontinuities which are generally considered to be steepened large amplitude Alfvén waves. Evidently, such an expectation is not realized with the end of the field vector moving randomly with a maximum excursion corresponding to a semi-circle with radius equal to B. In fact, since the direction of K is essentially radial, the minimum variance is likely to be associated with the sector structure which causes the field to point essentially outward at all times. As a consequence, the B vector appears to vary randomly over the surface of a hemisphere.
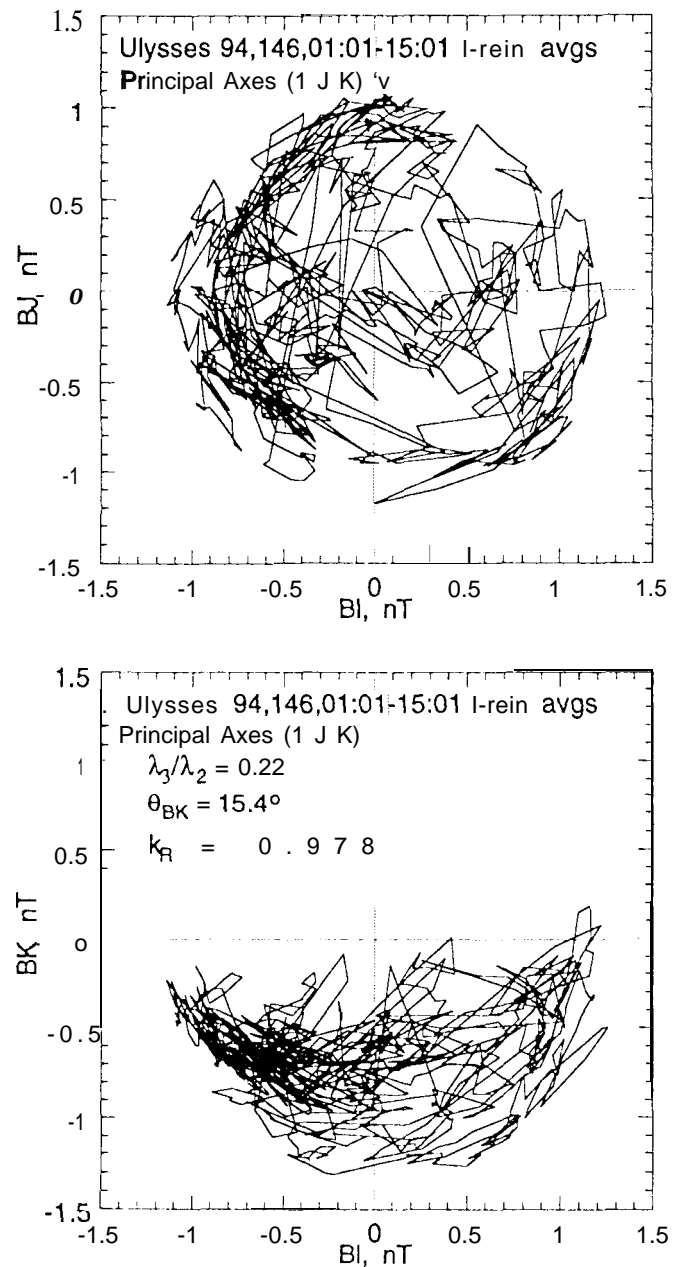

Fig. 5. Magnetic field fluctuations in principal axes.

This stochastic behavior of large amplitude Alfvén waves was investigated many years ago theoretically by Barnes (1981), when the characteristics of the in-ecliptic Alfvén waves had been revealed beginning with the comprehensive study by Belcher and Davis (1971), Barnes assumed a random walk of the field vector inside a sphere (or hemisphere) whose radius is equal to a constant field magnitude. He used a Fokker-Planck equation to derive a probability density (and integrated probability) of the angle between the initial and final positions of the field vector. The results are shown in Figure 6. The evolution of the two types of distribution is shown by plotting them at several intervals corresponding to a number of autocorrelation times (or scales).

We have carried out an analysis of this kind using observed field vectors. We began by computing the autocorrelation function of the angle, θ, between an arbitrary initial and final field orientation to determine the correlation time. The result is shown in Figure 7 for three different time intervals which essentially lead to the same results. The autocorrelation declines rapidly to e^{-1} after only 2 to 4 hours.
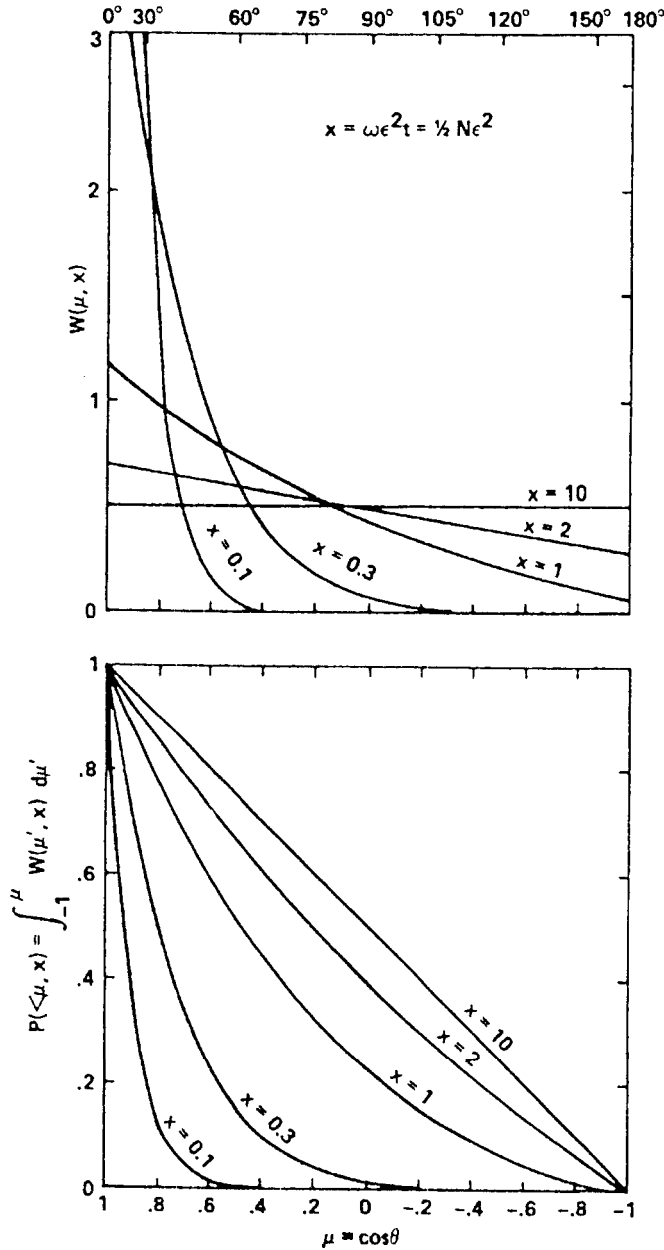

Fig. 6. Theoretical calculations of the probabilities of the angle between an initial and final field orientation (Barnes, 198 1).
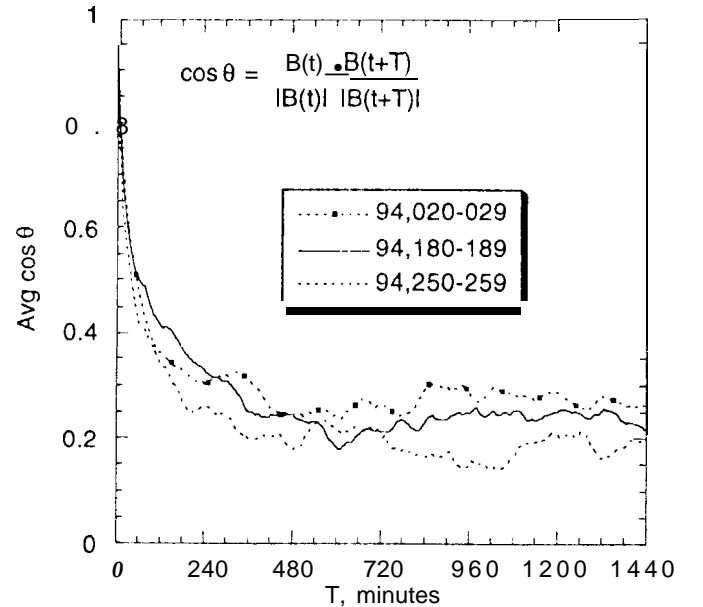

Fig. 7. Autocorrelation function,

A single interval was then analyzed over successively longer times between the initial and final vectors and the differential and integral probabilities were computed as shown in Figure 8 a, b. Comparisons of

Figures 6 and 8 show a close correspondence confirming the random walk of the field vectors over a spherical surface of constant magnitude.

We have carried out a large number of principal axis analyses which have produced the statistical results appearing in Figure 9. An important parameter which indicates how well-defined the K (smallest) eigenvector is, or the extent to which the variations are plane polarized (restricted to the IJ plane), is the ratio of the smallest to the intermediate eigenvalue, λ_3/λ_2. As a general rule, this ratio should be less than 0.3 -0.5 for the analysis to be considered as leading to a reasonably well-defined K vector. The histogram of λ_3/λ_2 shows this criterion was satisfied for most of the 1412 6-hour intervals of one minute averages that were run. One half of the cases have a ratio less than 0.4.

The radial component of the (unit) k vector is of interest because it could be interpreted as the direction of propagation of the waves. Most of the k vectors are nearly aligned with the radial direction. This result is borne out by the histogram of k_R. The distribution is strongly peaked near $k_R = 1$. Correction for the solid angle effect, which weights small values of k_R (large angles to r) more heavily, would only serve to strengthen this conclusion.

Successful principal axis analysis leads to the angle, θ_{Bk}, between the k vector and the field direction averaged over the analysis interval, The histogram of this angle has a most probable value of -20° and a mean of 33°. Thus, k is aligned with the radial direction rather than

Fig. 8. Observed probability densities.

with the field direction. This result contrasts with principal axis analyses of in-ecliptic Alfvén waves which typically indicate that the k vector is aligned with B.

Assuming that k is the wave direction of propagation, two contrasting arguments have been advanced. Hollweg (1 975) reasoned that the wave fronts would be "refracted" such that k would become parallel to r with increasing distance. (Actually, this effect occurs because the divergence of the solar wind stretches the wave front in the transverse direction.) Belcher and Davis (1971) suggested that propagation at art angle to B would lead to a variation in the magnitude of B (or coupling to the fast magnetosonic mode)
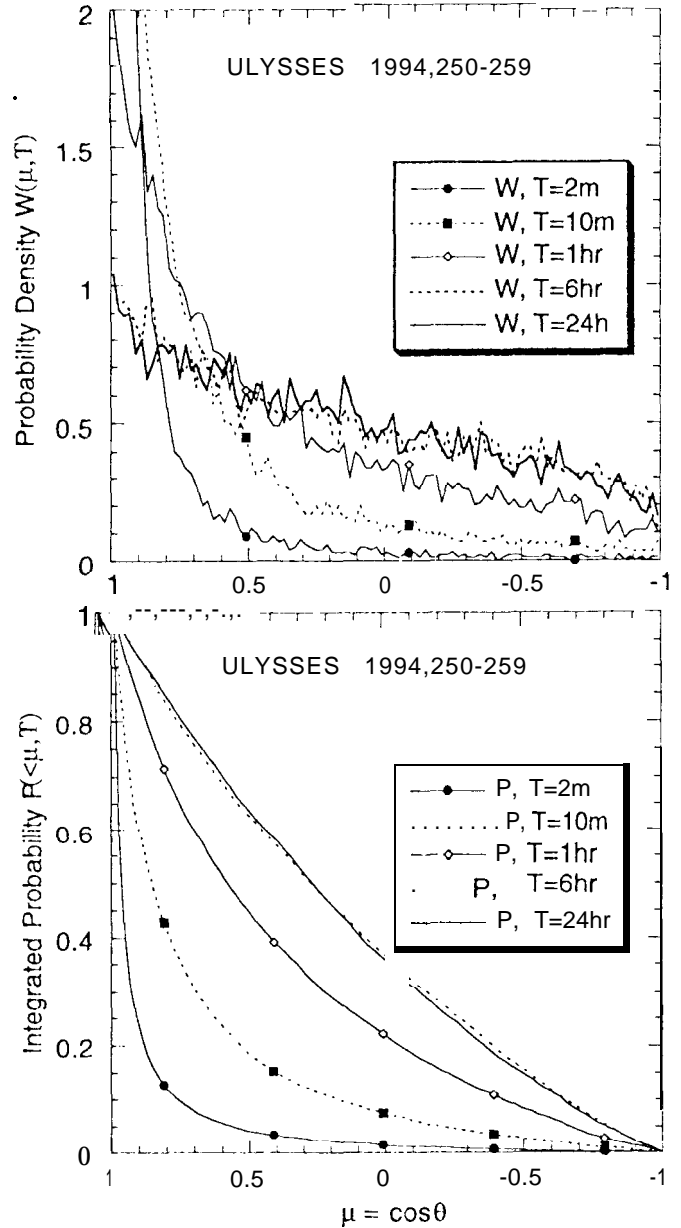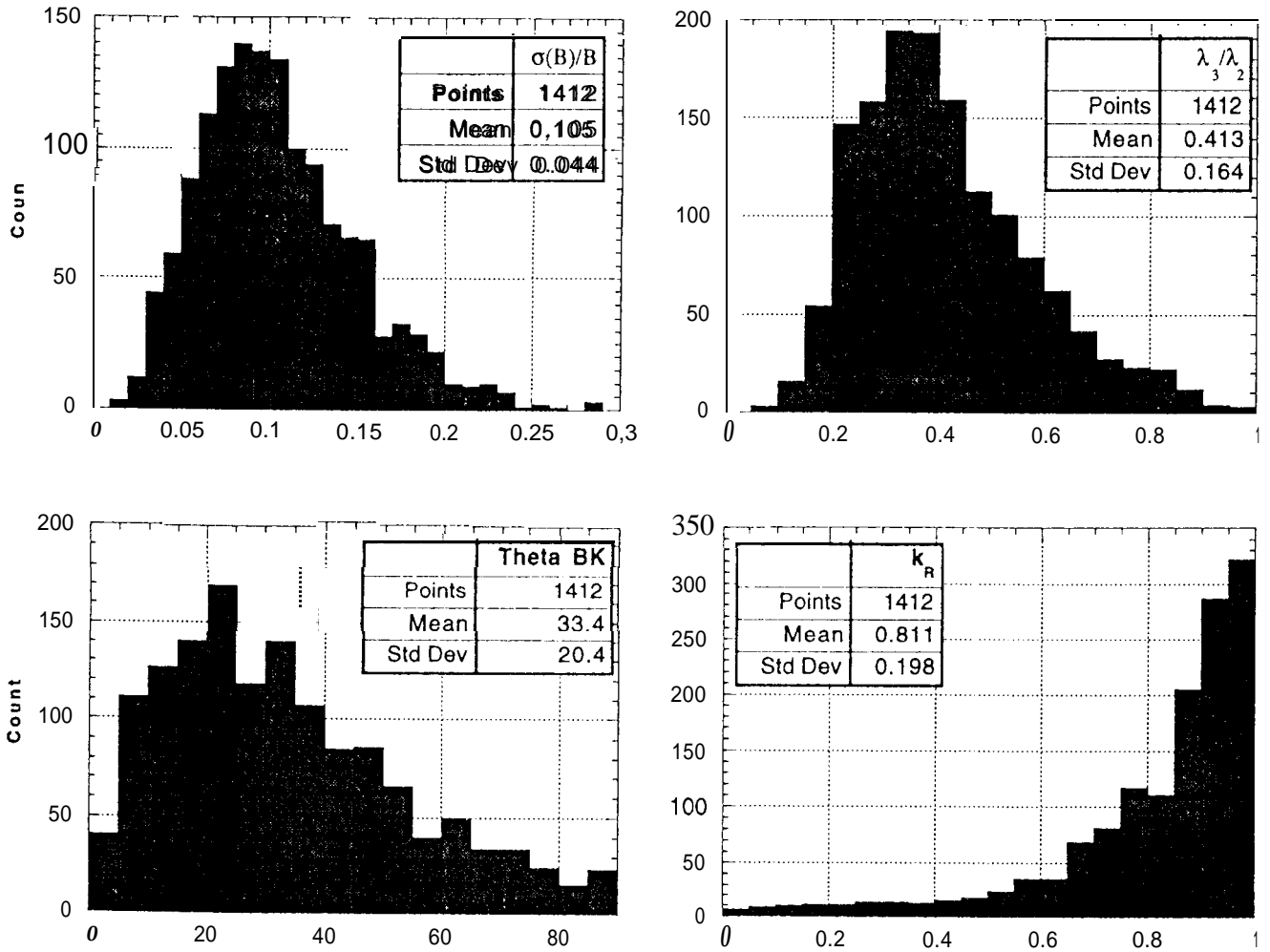
Fig. 9. Statistical results of principal axis analyses.

which would then be rapidly damped. Such issues evidently need to be revisited in light of the Ulysses results.

As just stated, variations in field magnitude are an important aspect of any wave study, possibly indicating the presence of magnetosonic modes. Figure 9 also contains a histogram of $\sigma(B)/B$, the ratio of the standard deviation to the field magnitude, which shows a most probable value and an average of --0.1 or, variations in B present at the $10\%/0$ level. Undoubtedly, some variations are caused not by waves but by structures such as small interaction regions associated with the high latitude microstreams and Pressure Balance Structures/PBS (for which the sum of the kinetic and magnetic pressures are constant).

MAGNETOSONIC WAVES

We have recently begun to analyze the high latitude fluctuations for evidence of magnetosonic waves. Such an undertaking is expected to be difficult in view of the lack of success in identifying magnetosonic waves in the in-ecliptic slow/fast wind. It is essential to be able to discriminate magnetosonic waves from microinteraction regions and PBS's, and to do so in the presence of the large amplitude Alfvén waves.

Both PBS'S and Alfvén waves, unlike magnetosonic waves, are characterized by a constant total pressure. Interaction regions involve increases in total pressure but typically appear at gradients (increases) in the solar wind speed and are readily identifiable. Although magnetosonic waves involve perturbations in velocity (δV) and, except for propagation along field lines, in the field direction (δB), the presence of the large variations in both associated with the Alfvén waves are thought to render analyses of the vector quantities of little use. For these reasons, we have chosen to concentrate our search on scalar quantities (p, B, P).

Another part of our strategy has been to concentrate on regions where reasonably large amplitude magnetosonic waves might be expected. obvious choices from this standpoint are the regions adjacent to, i.e., up- and downstream of, the microinteraction regions (Neugebauer *et al.*, 1995). In the ecliptic, classic examples of fast magnetosonic waves are the shocks that accompany CIR's at distances beyond -2 AU. The pressure pulse that forms at the interface between slow and fast wind drives waves into the upstream and downstream winds that eventually steepen into shocks. The weak interaction regions at high latitude are not accompanied by shocks but by small pressure pulses which presumably also radiate into the adjacent solar wind regions. In a sense, the high latitude interaction regions are not as highly evolved as those in the equatorial region at the same distance. It might be possible to take advantage of this slow evolution to identify and characterize magnetosonic waves in the Ulysses data.

The preliminary results based on this approach are encouraging. Figure 10 provides a representative example similar to many which have been identified so far. The plot contains B, p and total pressure, $P_T = 2nkT + B^2/8\pi$, over an interval of several days centered on the interface which is evident as the pressure pulse coinciding with the speed increase. Of particular interest are the increases and decreases in P_T up- and downstream of the interface. They are well correlated with changes in p and to a lesser extent with B.

The extended interval over which these variations occur is reasonable. If the variations originate near the Sun, where the interface presumably forms, they may have been propagating away from the interface for the several days it takes for the solar wind to reach Ulysses at several AU. At reasonable magnetosonic speeds, they could have propagated to distances such that they are seen a day or so before and after the interface is observed.

Fig. 10. Variations in pressure, density, and field magnitude in the vicinity of a high latitude interaction region,

The chief task now facing us is to make a positive and unambiguous identification, if possible, of these variations as magnetosonic waves. Since the variations may pass as small amplitude waves, we are looking for criteria based on the solutions obtained from a linear analysis (Alfvén and Falthammar, 1963; Landau and Lifschitz, 1960). The theory of large amplitude waves is also available (Barnes and Hollweg, 1974). We expect to resolve these issues in the near future.
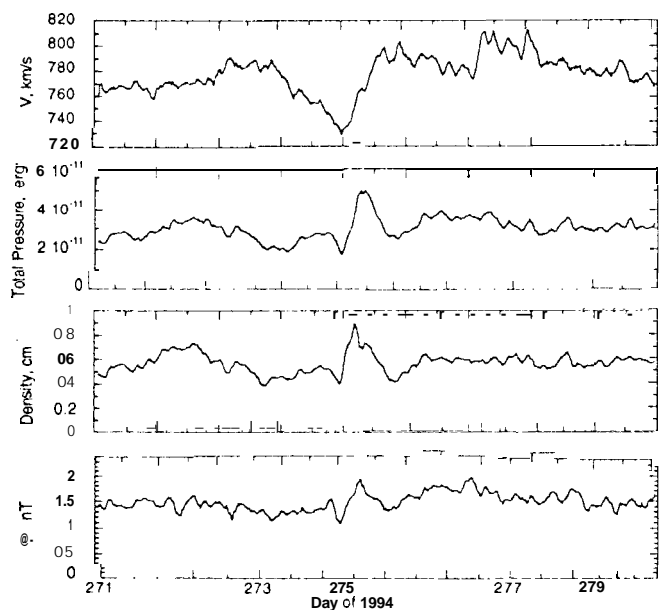
References

Alfvén, H. and C. -G. Falthammar, *Cosmical Electrodynamics*, 228 pp., Oxford University Press, Oxford (1963).

Barnes, A., Interplanetary Alfvénic fluctuations: A stochastic model, *J. Geophys. Res.*, **86, 7498-7506 (1981).**

Barnes, A. and J. V. Hollweg, Large amplitude Hydromagnetic waves, *J. Geophys. Res.*, 79, 2302-2318 (1974).

Belcher, J. W. and L. Davis, Jr., Large-amplitude Alfvén waves in the interplanetary medium, J. *Geophys. Res.*, **76, 3534-3563 (1971).**

Forsyth, R. J., T. S, Horbury, A. Balogh, and E. J. Smith, Hourly variances of fluctuations in the heliospheric magnetic field out of the ecliptic plane, *Geophys. Res. Let/., 23, 595-598(1 996).*

Goldstein, B. E., M. Neugebauer, and E. J. Smith, Alfvén waves, alpha particles, and pickup ions in the solar wind, *Geophys. Res. Lett., 22, 3389* (1995).

Hollweg, J. V., Waves and instabilities in the solar wind, Rev. *Geophys. Space Phys., 13, 263-289 (1975).*

Hollweg, J. V., Transverse Alfvén waves in the solar wind, J. *Geophys. Res.,* 79, 1539-1541 (1 980).

Jokipii, J. R., J. Kota, J, Giacalone, T. S. Horbury, and E. J. Smith, Interpretation and consequences of large-scale magnetic variances observed at high heliographic latitude, *Geophys. Res. Lett.*, 22, 3385-3388 (1995),

Landau, L. D. and E. M. Lifschitz, *Electrodynamics of Continuous Media,* Addison- Wesley, New York (1 960).

Neugebauer, M., B. E. Goldstein, D. J. McComas, S. T. Suess, and A. Balogh, Ulysses observations of microstreams in the solar wind from coronal holes, *J. Geophys. Res.*, 100, 23389 (1 995).

Smith, E. J., M. Neugebauer, A. Balogh, S. J, Bame, G. Erdos, R. J. Forsyth, B. E. Goldstein, J. L. Phillips, and B. T. Tsurutani, Disappearance of the heliospheric sector structure at Ulysses, *Geophys. Res. Lett., 20, 2327-2330(1 993).*

Smith, E. J., A. Balogh, M. E. Burton, G. Erdos, and R. J. Forsyth, Results of the Ulysses fast latitude scan: Magnetic field observations, *Geophys. Res. Lett.*, 22, 3325-3328 (1995a),

Smith, E. J., A, Balogh, M. Neugebauer, and D. McComas, Ulysses observations of Alfvén waves in the southern and northern solar hemispheres, *Geophys. Res. Let/.,* 22, 3381-3384 (1995b).

Sormerup, B. U. O. and L. J. Cahill, Magnetopause structure and attitude from Explorer 12 observations, *J. Geophys. Res.,* 72, 171-183 (1967).

Tu, C. Y. and E. Marsch, On the nature of compressive fluctuations in the solar wind, *J. Geophys. Res.*, 99, 21,482-21,509 (1994).